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Effect of Shear Wave Propagation on Estimation of Heating Distribution by High-intensity Focused Ultrasound Using Acoustic Radiation Force Imaging

音響放射力イメージングを利用した HIFU の加熱分布推定における剪断波伝搬の影響

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1. Introduction

High-Intensity Focused Ultrasound (HIFU) can treat tumor tissue in a minimally invasive manner. In this treatment method, ultrasound is generated outside the body and focused on a target tissue to induce thermal coagulation.

The position of ultrasonic heating in the tissue can be shifted from the focal point in water toward the HIFU transducer due to acoustic phenomena such as ultrasonic refraction, scattering, tissue absorption, and so on. The shift can be further enhanced by higher harmonics generated through nonlinear propagation. Therefore, it is very important to estimate the actual region of heating before HIFU treatment to ensure the safety and efficacy of the treatment. Acoustic radiation force impulse (ARFI) imaging using HIFU[1)] is a method to make such estimation possible. In the method, the distribution of ultrasonic absorption is estimated by assuming that the absorption is propotional to the ultrasonic attenuation. However, the distribution of tissue dispalcement induced by the acoustic radiation force expands as the shear wave propagates[2)]. In this study, the effect of the shear wave propagation on the estimation of heating distibution is investigated by changing the duration of ultrasonic exposure in HIFU radiation force imaging.

2. Materials and Methods

2.2 HIFU radiation force imaging

The acoustic radiation force F generated in soft tissues by focused ultrasound is given by,

$$|F| = \frac{2\alpha I}{c} \tag{1}$$

where α is the acoustic attenuation coefficient of the tissue, c is the tissue's sound speed, and I is the acoustic intensity.

The acoustically generated heat Q due to HIFU exposure can be expressed as,

$$Q = 2\alpha_a I \tag{2}$$

where α_a is the acoustic absorption coefficient. Assuming that the attenuation is proportional to the absorption, the right hand sides of equation (1) and (2) are considered to be proportional. Therefore, the heat distribution can be estimated from the displacement distribution assuming the uniformity of the tissue in a region of interest (ROI).

2.1 Experimental setup and Sequence

Experiments were performed in an acrylic tank, containing degassed water and a chicken breast tissue which had been soaked in degassed saline at room temperature, as shown in **Fig. 1**. The water tank was equipped with a 256-channel HIFU transducer with both focal length and outer diameter of 120 mm, driven at 1 MHz by a driving system (Microsonic). In the central hole of the transducer, there was an imaging probe at a center frequency of 3.5 MHz. It was connected to an ultrasound imaging system (Verasonics) to acquire RF data. The distance from the surface of the probe to the geometric HIFU focus was 68 mm.

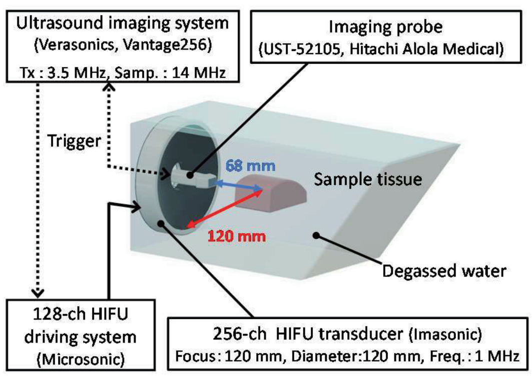

Fig. 1 Schematic of experimental setup.

Fig. 2 shows the ultrasonic exposure sequence. The upper half part shows the sequence of HIFU burst wave exposure. The other half part shows the imaging sequence. RF data was acquired by a single plane wave transmission before and after the HIFU exposure. An interval of 400 μs was set after the HIFU burst to reduce the interference of HIFU with

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ultrasound imaging. The axial displacement is calculated by applying the autocorrelation method[3] to the frames before and after the HIFU exposure. In this study, the total acoustic power (TAP) of HIFU was changed in the range of 90 - 210 W, and the HIFU duration in the range of 100 - 1000 μs.

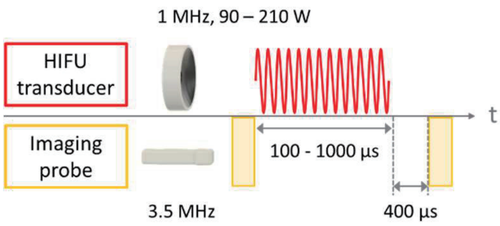

Fig. 2 Ultrasound exposure sequence.

3. Results and Discussion

Fig. 3 shows a B-mode image and distributions of displacement after HIFU exposure at a TAP of 210 W with a duration of 100 - 1000 μs. Each distribution was created by averaging the results obtained seven times, and the value of displacement was normalized. Comparing the subfigures (b), (c), and (d), it is seen that the displacement region which represents estimated heating area by HIFU expanded as the HIFU burst duration increased. **Fig. 4** shows normalized axial displacement profiles at the center position of the lateral axis as a function of depth away from the transducer. This result demonstrates that the displacement in the shallower region, that is, the region closer to the transducer, increased as the HIFU duration becomes longer, presumably caused by the shear wave propagation.

Fig. 5 shows the change in the peak displacement as the TAP increased. The blue square represents the peak displacement after 500 μs HIFU exposure at each TAP, the blue dotted line represents the 2-order polynomial fitting. The displacement increased nonlinearly at the TAP range up to 210W. Notice that the displacement at 210 W, it was about 1.5 times the linear case. In the simulation[4] for the heating distribution Q by HIFU, however, the peak of Q at 210W was more than three times the linear case. The reason for the difference is probably due to the spatial averaging effect mainly caused by the propagation of shear waves for 900 μs from the beginning of HIFU exposure to the RF data acquisition.

4. Conclusion

In this study, the effect of shear wave propagation on the estimated distribution of HIFU heating was investigated. The results show that it is required to consider the effect on both the estimated region and the peak value.

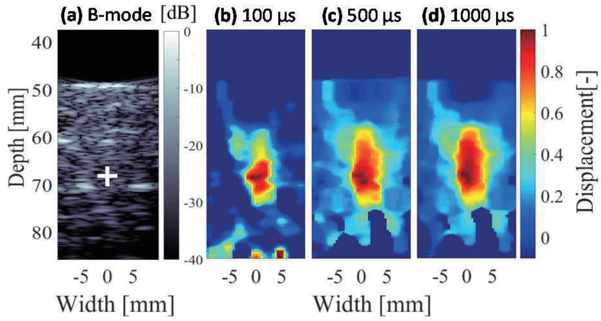

Fig. 3 Set of (a) B-mode image and distributions of displacement after the start of HIFU exposure at a TAP of 210 W with a duration of (b) 100, (c) 500, and (d) 1000 μs.

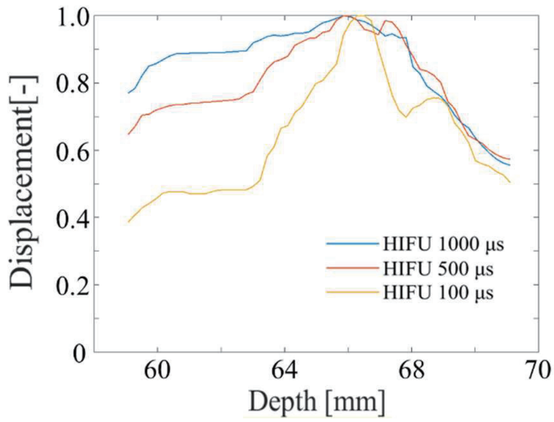

Fig. 4 Normalized axial displacement profiles at the center of the lateral axis.

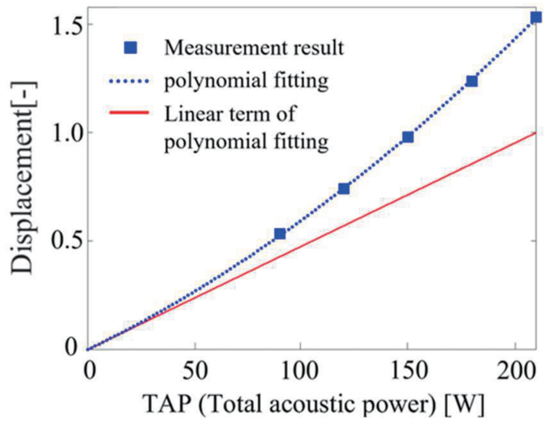

Fig. 5 Profiles of peak displacement after 500 μs HIFU exposure as a function of TAP.

References

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